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Climatology Study of World Airports in the Context of Wake Vortex Behaviour Class

March 2002

P. Agnew and D.J. Hoad

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Met Office , Forecasting Products , Room R203 , London Road , Bracknell , Berkshire ,RG12 2SZ, United Kingdom

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The Met Office
Forecasting Development
Room R321
London Road
Bracknell
RG12 2SZ
United Kingdom

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Assessment of
Wake Vortex Safety

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Climatology Study of World Airports in the Context of Wake Vortex Behaviour Class

P. Agnew and D. J. Hoad
Met Office, Bracknell, UK

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Abstract

Atmospheric conditions play a key role in the evolution of aircraft wake vortices. Earlier work in S-Wake has proposed the introduction of discrete 'wake vortex behaviour weather classes' (WVBC) in which vortices are expected to exhibit differing evolution characteristics. As part of a broader study we have established climatologies with respect to these WVBC for a variety of airports world-wide. The Met Office Site Specific Forecast Model was used to calculate vertical profiles of meteorological variables over a seven year period. Synoptic data from each site and forcing data from the ECMWF ERA-15 re-analysis project were used as input to the model. The profiles were used to evaluate the mean WVBC at each site on pressure levels up to a value corresponding to a height of around 2km. It is found that at many airports, WVBC which favour the rapid dissipation of wake vortices are prevalent for in excess of 30% of the time. The implications of these results for future wake vortex separation rules are discussed.

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1. Introduction

1.1 The Wake Vortex Problem

The increasing capacity demands at major airports throughout the world continue to drive research in the civil aviation community into ways of increasing the number of hourly aircraft movements in a safe manner. At busy airports the frequency of movements is restricted by aircraft separation rules imposed due to safety concerns associated with wake vortex encounters. The current separation rules have been highly effective in reducing wake vortex encounters, however there are situations where they appear overly conservative. As a result there is considerable interest in developing a greater understanding of wake vortex evolution in order that a more flexible approach to imposing separations can be implemented. The European initiative S-Wake is a multi-activity research programme aimed at addressing these issues and comprises a variety of both experimental and theoretical studies. One important strand is concerned with understanding how local meteorological conditions influence the evolution of vortices. If meteorological conditions can be identified in which wake vortices are known to either dissipate quickly or be swept away from the path of following aircraft, and if those conditions can be reliably forecast sufficiently far ahead, then there exists the basis for a more flexible implementation of aircraft separation rules, which could lead to valuable increases in the frequency of movements in and out of busy airports.

Earlier work in this area by Frech et. al. [1] concentrated on identifying and defining a small number of so-called 'wake vortex behaviour classes' (WVBC) with which a given level of risk can be associated. It was deemed desirable to introduce the concept of discrete classes (contrasting with the continuous range of meteorological conditions) in order that air traffic controllers should be able to work with a relatively small number of separation classes, as at present, dependent on the WVBC prevalent at any given time. The present report describes work performed under Task 1.3, Work Package 1 of the S-Wake programme and is concerned with establishing a climatology with respect to WVBC for major airports throughout the world.

1.2 Site Selection

Sites were selected where wake vortex separation rules currently impose a limitation on aircraft movements or where it was thought relatively likely that a prospective 'very high capacity aircraft' might be deployed. Some of the airports originally selected were eliminated from the final study because there was no observational data available for the time period of interest. Airports eliminated in this way included the Chinese airports Shanghai and Beijing, and the Japanese airports Osaka Kansai and Tokyo. Toulouse was added to the final site list for use in the SYAGE validation study.

1.3 Report Overview

The work of Frech et. al. [1] has identified four independent 'wake vortex behaviour' classes (WVBC) in which vortices have identifiably different evolution characteristics. These classes are reviewed below in section 2. In order to determine the meteorological conditions at each site we have utilised the Met Office Site Specific Forecast Model (SSFM), together with synoptic (i.e. winds, temperatures, pressures etc.) observations and a consistent set of forcing data. This model and its associated input data are briefly described in section 3. A more complete description of the SSFM can be found in reference [2]. The data analysis techniques and methods of evaluation of WVBC parameters are described in section 4. The results of this analysis are presented in section 5 (with figures in appendices C and D) in the form of a statistical analysis showing the frequency of occurrence of each WVBC as a function of height. In section 6 we give an overview of the main findings, together with a discussion of our interpretation of these findings. The implications of these results are discussed in section 7 and some conclusions regarding the implications for further wake vortex research are set out. Finally in section 8 a summary of the report is presented.

2. Review of Wake Vortex Behaviour Classes

Frech et. al. [1] have provisionally described the criteria for ascribing WVBC under given meteorological conditions, based on a combination of Richardson Number and vertical wind shear. The classes are designated turbulence, stable stratification, wind shear, null and cross wind. The first four are mutually exclusive. However the conditions for the cross wind class may be satisfied at the same time as those for either the turbulence, stable stratification or wind shear classes. The five categories are described fully below:

(i) Turbulence

The turbulence class is characterised by a Richardson Number, $R_i \leq 0.25$. In these conditions the wake vortex is expected to rapidly dissipate via its interaction with the turbulent atmosphere.

(ii) Stable Stratification

This class has Brunt-Väisälä frequency $N > 0.014\ s^{-1}$ and $R_i \geq 1.0$. Enhanced decay is anticipated, via the mechanism described by Holzäpfel [3]. However there also exists the possibility of reduced vortex descent velocity or even rebound due to the buoyancy characteristics of the ambient air.

(iii) Wind Shear

Weather conditions in this class are described by a vertical wind shear and an intermediate Richardson Number in the range $0.25 < R_i < 1.0$. Under these weakly turbulent conditions no enhanced vortex decay is anticipated. Furthermore the presence of wind shear offers the possibility of vortex

rebound, since it is now generally accepted that a low level jet often favours subsequent lift of a vortex. No threshold value of wind shear was given by Frech et. al. as a criterion for this class and it was stated that the shear profile may be important. The criterion for this class is therefore currently determined solely by the range of R_i stated above.

(iv) Cross Wind

This class differs from the others in that it is site and runway dependent. In the presence of a cross wind a portion of the wind velocity vector is added to that of the descending vortices, resulting in downwind advection of the vortices. In many cases this reduces the risk of a wake vortex encounter because the vortices are swept off of the runway. However if a parallel runway is present the level of risk may increase due to the possibility of one or both vortices being blown onto the adjacent runway. The criterion for this class outlined by Frech et. al. [1] is that the wind has a component perpendicular to the runway which is sufficient to sweep the vortices from the path of the following aircraft. A limiting value of $0.6ms^{-1}$ was recommended. This value was deduced from a simple theoretical model of the entire vortex being swept laterally at a speed equal to the cross wind and uses appropriate values for the aircraft wingspan, approach speed and current separations. A significantly higher value of $3.11\ ms^{-1}$ (equivalent to 6 knots) has been suggested from experimental studies [4]. This value has been shown [4] to be effective in sweeping vortices away from single runways. In this report we have used this higher value. Additional work is required to give a detailed explanation of the discrepancy between these two values. We emphasise that any further statements regarding the safety or otherwise of cross wind conditions cannot be made without a detailed study of each particular site, runway configuration and runway usage. This point is elaborated on further in section 6.3.

(v) Null Class

Finally, any conditions not fulfilling the criteria for any of the above four classes are assigned to a null class, which is expected to be neutral with respect to wake vortex risk.

3. Meteorological Data Generation

In order to determine the WVBC at a given location it is necessary to determine the value of the relevant meteorological parameters as a function of altitude. We have used the Met Office Site Specific Forecast Model (SSFM) to generate these profiles. The SSFM is essentially a single column version of the Met Office Unified Model (UM) which is routinely used for producing global weather forecasts. The SSFM has increased vertical resolution near the surface, with 54 levels up to an altitude of around 2km. This high resolution makes it ideal for studying processes occurring in the boundary layer.

The initial conditions for a forecast run are supplied by a combination of actual surface synoptic observations and upper air forcing data from the ECMWF Re-analysis Project, ERA-15 [5]. The synoptic data were obtained from the national meteorological services of individual countries and the Met Office archives. The synoptic data that was used for each site is listed in Appendix A. In most cases hourly, 3 hourly or 6 hourly data was available throughout the period investigated. At some sites, there were large gaps in the synoptic data (such as at Hong Kong, Munich and Singapore). Oslo Gardermoen and Munich airports have been built since the period of study, so synoptic observations were taken from the nearest observing stations for these sites.

The synoptic observation data were quality checked by scanning the observation values. Very high (above about 50°C) or very low (below about –40°C) values of temperature and dewpoint were discarded. Moderately low and moderately high values of temperature and dewpoint were flagged, as were high values of wind speed (above 50 knots), and occurrences of large temperature gradients. These observations were then compared to neighbouring values by a human analyst and discarded if the quality was doubtful.

The ERA-15 project involved the re-analysis of archived meteorological data to produce a new and validated 15 year set of assimilated data for the period December 1978 to February 1993. The main advantage of such a data set is that it is produced consistently and is independent of any changes made to forecast models over the period. The consistency of the data set makes it ideal for applications involving longer-term climatological studies, such as the present investigation. The SSFM assimilates the synoptic data and 'nudges' the ERA-15 forcing data towards values at screen level to produce a set of initial conditions at the forecast site which is consistent with both the local measurements and conditions at other locations. The temporal resolution of the ERA-15 data is 6-hourly.

Additionally information describing the topography (including height of land, surface roughness and land use) in the neighbourhood of the airport is used in the SSFM. This will contribute to the differences between the climatologies of pairs of airports which are relatively close to each other, as will the differences in synoptic data (where the latter are available).

It was originally envisaged that the present climatological study would attempt to utilise the full 15 years' worth of model output, consistent with the ERA-15 forcing data. However retrieving this forcing data from ECMWF archives proved to be a much slower process than anticipated, partly due to faulty processes at ECMWF and hence beyond our control. The present study has therefore utilised 7 years' worth of climatological data. We do not believe that this presents a limitation because, as will be discussed in section 5.1, the WVBC determination for a given site seems to converge quite quickly.

4. Data Analysis

4.1 Evaluation of WVBC Criteria

The data analysed consists of hour by hour values of meteorological variables over the 7 year period 1979 to 1985 for each of the 45 sites studied. The sites studied are listed in appendix A. Meteorological data are given by the SSFM at 77 pressure levels, although we have only utilised the first 54 levels. These levels are listed in appendix B, together with an approximate conversion to altitude. The conversion is only intended as a rough guide, since any accurate conversion between pressure level and height does of course involve the vertical temperature profile, which varies from case to case.

The SSFM returns a large number of meteorological parameters. The WVBC criteria given by Frech et. al. [1] require only the u and v components of wind and the potential temperature θ. These three variables are evaluated by the model on each of the 54 pressure levels. In addition we have also used the model values of surface temperature and pressure, since these are required to perform the conversion from pressure levels to altitude.

Determination of the WVBC requires knowledge of the Richardson Number R_i and the Brunt-Väisälä frequency N. These parameters were evaluated from the wind components and potential temperature at each level according to the following equations:

$$N^2 = \frac{g}{\theta}\left(\frac{\partial\theta}{\partial z}\right) \quad , \tag{1}$$

$$R_i = \frac{N^2}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \quad . \tag{2}$$

The derivatives in these expressions were evaluated using an algorithm utilising a three-point Lagrangian interpolation scheme. They are evaluated with respect to altitude and for this purpose the pressure level to height conversion must take into account the variation of temperature with altitude. This is done via a form of the hydrostatic equation, expressed in terms of height, potential temperature and the Exner pressure, Π. The relationship between changes in height Δz and the change in Exner pressure $\Delta\Pi$ is

$$\Delta z = \frac{-C_p\theta}{g}\Delta\Pi \quad . \tag{3}$$

In this equation C_p is the specific heat capacity at constant pressure of dry air, 1005 $JKg^{-1}K^{-1}$ and g is the mean acceleration due to gravity at the Earth's

surface, 9.81ms^{-2}. The Exner pressure is related to the actual pressure p expressed in SI units via

$$\Pi = \left(\frac{p}{10^5}\right)^{\kappa} \quad . \tag{4}$$

The constant κ is given by

$$\kappa = {}^{\gamma - 1}\!/_{\gamma} = 0.2856 \quad , \tag{5}$$

where γ is the ratio of specific heats for dry air.

4.2 Evaluation of Cross Wind Criterion

In order to determine the crosswind characteristics at a given level we adopt the following procedure. Assume the runway has an orientation defined by direction cosines (α, β), where α is defined with respect to a north pointing axis and β with respect to an easterly axis. Let the wind vector $\underline{V}$ have direction cosines (α', β'). The component of wind perpendicular to the runway is then

$$V_{cross} = |\underline{V}|\left(1 - (\alpha\alpha' + \beta\beta')^2\right)^{1/2} \quad . \tag{6}$$

Our criterion for the cross wind class is that V_{cross} > 3.11ms^{-1} (6 knots). According to Halsey [4] this value is sufficiently high that all the vortices observed in an experimental study of ~100,000 wake vortices were swept well clear of the runway. As mentioned earlier, any determination of the safety or otherwise of the cross wind class requires a detailed study of runway configuration and usage at a particular site and this is beyond the scope of the present work. However it was deemed important to give an indication of the degree to which cross winds might play a significant role at a number of sites. The sites chosen for this additional analysis were London Heathrow, Frankfurt, Paris Charles de Gaulle, Toulouse and Amsterdam Schiphol airports. The following table identifies the runways which were considered in the analysis for each airport and their orientation.

Airport	Runway Identifier	Orientation
Heathrow	09L/27R	89.7°
Schiphol	01L/19R	3.0°
Charles de Gaulle	09L/27R	85.0°
Frankfurt	07L/25R	69.4°
Toulouse	15L/33R	143.0°

Table 1. Runway orientations for airports selected for cross wind study

5. Results

5.1 Null, Turbulence, Stable Stratification and Shear WVBC

We have analysed meteorological conditions at 45 sites, each hour of the day for seven years, at each of 54 pressure levels extending from the surface up to an altitude of around 2km. The results for each site are presented in appendix C. The outcome of each single analysis has been to assign a weather class using the criteria described in section 2. With such a large quantity of data an economic means of presenting the results is required. We have therefore presented the result for each of the four classes null (blue), turbulence (green), stable stratification (red) and wind shear (yellow) on a single colour plot. The horizontal extent of each band shows the proportion of time spent in each WVBC. To give a concrete example, if a given figure indicates a value of 23% for the turbulence class at a height of 500m, this means that 23% of the total number of hours analysed over the entire 7 year period found meteorological conditions satisfying the criteria for the turbulence WVBC at this height.

As discussed in section 4, the SSFM calculations were performed on well-defined pressure levels. Conversion of the results to a height scale requires a knowledge of the vertical temperature profile, which is clearly different for each case. However in order to facilitate easier interpretation of the results it seemed desirable to translate the pressure levels to a corresponding mean height. The vertical axis in the figures is therefore shown as height, in metres, and is to be understood to be an approximate value. This approximate conversion was obtained by averaging the height at each pressure level for each site on one particular day. The results of this exercise are shown in appendix B.

It was originally intended to produce climatologies based on a 15 year period. However practical difficulties in retrieving forcing data from ECMWF limited us to a seven year study. In order to confirm the value of this shorter study we examined the convergence of the WVBC plots after every year up to the seventh. In fact the results converge rapidly, with the plots after just two years being virtually indistinguishable from those after the full seven year period.

5.2 Cross Wind WVBC

For the five sites London Heathrow, Frankfurt, Paris Charles de Gaulle, Toulouse and Amsterdam Schiphol we have also calculated the proportion of time spent in the cross wind weather class. These results are shown in appendix D, figures D1 to D5. The upper figure shows the proportion of null, turbulence, stable stratification and wind shear classes (identical to the plots in appendix C but repeated here for convenience) and the lower figure gives the results for the crosswind. As discussed in section 4.2, a threshold value of $3.11 ms^{-1}$ was used.

5.3 Meteorological Parameter Variation

A number of modelling studies focussing on wake vortex-atmospheric interactions have been performed in recent years, both as part of S-Wake and within the broader aviation community. Having compiled a large body of information regarding typical values of atmospheric parameters it may prove useful to the modelling community to provide an indication of some of the more useful ones. For each of the five locations listed above we have therefore calculated mean values of Richardson number, the square of the Brunt-Väisälä frequency N^2 and the shear variation, S, defined by

$$S = \left(\left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 \right)^{1/2} . \qquad (7)$$

A set of cumulative mean values was calculated for each of the seven years analysed. In order to illustrate the range of values we have plotted each set with a different symbol. The results are shown in appendix E, figures E1 to E5. Note that due to its large variation, the natural logarithm of the shear is plotted rather than the shear itself. Therefore the variation over the years for these graphs appear smaller than for the other parameters.

6. Summary of Results

6.1 General Observations

We begin an analysis of the results by describing and interpreting some readily apparent features of the figures in appendix C which are common to the majority of sites:

(i) The turbulence class is invariably dominant at the surface and decreases in frequency with increasing altitude. This is consistent with the usual boundary layer model of turbulence being generated close to the surface.

(ii) The wind shear class rises to a maximum within a few hundred metres of the surface and thereafter generally decreases in frequency with increasing altitude. This pattern is consistent with typical wind profiles in the boundary layer and simple theoretical models, such as a logarithmic wind speed profile.

(iii) The stable stratification class is generally weak near the surface and becomes increasingly more frequent with increasing altitude. This is consistent with the fact that the surface is the main source of heat flux into the atmosphere at low levels, leading to greater levels of convection closer to the surface and more frequent stable stratification at greater altitudes.

6.2 Groupings of Qualitatively Similar Sites

Going beyond these broad generalisations it is possible to sub-divide the various sites into groups having common characteristics. The following table shows one possible set of groupings for some of the European and North American sites, based purely on a qualitative appraisal of the figures in appendix C.

Heathrow Gatwick Schiphol Toulouse Frankfurt Charles de Gaulle Orly Brussels Luxembourg	Memphis Indianapolis Chicago Dulles Newark	Le Lamentin Le Raizet Miami	Atlanta Dallas/Fort Worth Toronto	Oslo Anchorage

Table 2. Some groupings of airports exhibiting qualitatively similar WVBC distributions

Patterns between other smaller groups of sites can also be discerned. The European sites listed in the first column are characterised by all of the features listed in the previous section and in this sense might be described as 'typical'. As one would expect, sites having common geographical and meteorological features share common features in their WVBC distribution.

6.3 Cross Wind WVBC

The cross wind weather class was only diagnosed for five sites and so only comments of limited generality can be made. We stress the point made earlier that the consequences of the cross wind class at any given site can only be determined with a careful study considering other runways and runway usage. As expected, the proportion of time spent in the crosswind WVBC increases rapidly with increasing altitude in the first 500m or so and then increases more slowly with further increases in height. For London Heathrow, Amsterdam Schiphol and Paris Charles de Gaulle the value adjacent to the ground is around 30-40%, whilst for Toulouse and Frankfurt it is around 15%. For all of the sites the value at higher altitudes is in the vicinity of 60%.

7. Discussion

7.1 Evaluation of Safer Meteorological Conditions

It is worthwhile re-stating the key aim beyond this climatological study. If meteorological conditions can be identified in which wake vortices are known to dissipate quickly or be swept away from the flight path of a following aircraft, and if those conditions can be reliably forecast sufficiently far ahead, then there exists scope for the implementation of more flexible aircraft separation rules. The aim of this climatological study has been to identify the relative frequency of occurrence of each type of WVBC. Having performed this analysis we are therefore in a position to assess the frequency with which safer meteorological conditions occur.

Considering the crosswind class, the results for the five sites studied show that for altitudes above around 500m, the criterion is satisfied for about 60% of the time. However in order to allow a reduction in separation it is necessary that safe conditions prevail all the way down to the surface. Frech et. al. [1] state that the turbulence and stable stratification WVBC offer safer conditions (although we will discuss the latter class further below). In many of the sites studied these two WVBC taken together occur around 30% or more of the time, over the full range of altitude considered (approximately 0 to 2000m). In the range 0 to 500m these two classes typically occur for at least 40% of the time. It is likely therefore that a safe weather class is prevalent over the entire glide slope for a proportion of the time somewhere between 40 to 60%. The implication of this is that, providing the following aircraft fly on the same track, there is scope for reducing separations for a corresponding proportion of the time.

7.2 Re-evaluation of WVBC

The WVBC outlined by Frech et. al. [1] were intended as provisional definitions and may need to be revised in the light of on-going research. In particular the stable stratification class may require a more detailed examination. Whilst numerical simulations, such as the recent work of Holzäpfel et. al. [3], suggest that strong stable stratification can lead to shorter vortex lifetimes, other evidence (see for example [6]) indicates that weaker stable stratification has relatively little effect on wake vortex dissipation but may actually increase the lifetime. Furthermore it also promotes increased vortex buoyancy, which can enhance the chance of a wake vortex encounter. It is not possible to reconcile both of these aspects of stable stratification within a single safety class. This is an area where more work is required and may result in a sub-division of this WVBC.

With regard to the cross wind weather class, the pertinent problem is in determining a suitable threshold. Theoretical considerations dictate that under a set of carefully prescribed conditions, a vortex will move horizontally with the component of the undisturbed wind vector perpendicular to the vortex. The effect of the fact that the actual conditions differ from those

idealised conditions can be quantified, and this factor must be taken into account when considering any reductions in separations. Another issue is the fact that the wind used should ideally be averaged over both space (horizontally, over the separation of the two aircraft, and vertically, taking into account both the vertical extent of the vortex and the distance through which it descends between the passage of the two aircraft) and time (the time between the passage of the two aircraft). Therefore in practice a single, appropriate wind value can never be measured. The empirical approach takes into account the difference between the averaged wind which governs the movement of the vortex, and the measured wind, which can be temporally averaged but has not been spatially averaged. This difference will be a major factor in explaining the discrepancy between the theoretical threshold of 0.6 ms^{-1} and the empirical figure of 3.11 ms^{-1}.

From this it is clear that if one has appropriately averaged wind measurements, such as could be obtained from aircraft themselves, the threshold lies somewhere between the two figures. Nevertheless, in producing graphical representation of the dependency of the threshold on height, the value of 3.11 ms^{-1} has been used. The scope for gains in capacity might well be significantly higher than the graphical representations in appendix D, based on this conservative value, suggest.

8. Summary

We have conducted a climatological study of 45 airports around the world. The Met Office Site Specific Forecast Model, using synoptic observations and forcing data from the ERA-15 re-analysis project, was used to generate vertical profiles of meteorological variables up to an altitude of around 2km. These were based on seven years' worth of data, from 1979 to 1985. The profiles were analysed to produce averaged 'wake vortex behaviour class' (WVBC) distributions at each level. The crosswind class offers the greatest potential for potential gains since at altitudes greater than around 500m the class criterion is satisfied for around 60% of the time. The combination of turbulence and stable stratification classes potentially offer safer conditions for around 40% of the time within 500m of the surface. The overall results demonstrate that at many airports, weather conditions which are conducive to more rapid dissipation or sweeping away of wake vortices are prevalent for between 40 to 60% of the time. This suggests that there may be scope for considerable gains in aircraft movements if a more flexible aircraft spacing system were to be introduced. This would require the ability to produce accurate forecasts of the WVBC in the vicinity of the airport, possibly combined with reliable monitoring of actual wake vortex behaviour.

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Appendix A List of sites and details of synoptic data used

Number	Airport code	Airport name	Synoptic data from Met Office archives	Synoptic data obtained from national meteorological services
00	ENGM	OSLO GARDERMOEN	every 6 hours, taken from Oslo Fornebu station, 33km from site	
01	EGLL	LONDON HEATHROW	every 3 hours	
02	EGKK	LONDON/ GATWICK	every 3 hours	
03	EHAM	AMSTERDAM SCHIPHOL	every 3 hours	
04	EBBR	BRUXELLES	every 3 hours	
05	ELLX	LUXEMBOURG	every 3 hours	
06	LFPO	PARIS ORLY		every 3 hours
07	LFPG	PARIS CHARLES DE GAULLE	every 3 hours	
08	LFBO	TOULOUSE BLAGNAC	every 3 hours	
09	LEBL	BARCELONA	every 3 hours	
10	LEMD	MADRID BARAJAS	every 3 hours	
11	EDDF	FRANKFURT	every 3 hours	
12	EDDM	MUNICH	every 12 hours from Jan 1985, taken from Munich Reim station, 26 km from site	
13	LIML	MILANO LINATE	every 3 hours	
14	LIRF	ROMA FIUMICINO	every 3 hours	
15	VIDP	NEW DELHI PALAM		hourly
16	VABB	BOMBAY SANTACRUZ	every 6 hours	
17	VHHH	HONG KONG		hourly data available from 13/6/1979-31/8/1983,

				and 6/9/1984-31/12/1985
18	VTBD	BANGKOK DON MUANG	every 6 hours	
19	WMKK	KUALA LUMPUR SUBANG	every 6 hours	
20	WSSS	SINGAPORE CHANGI		hourly Jul1981-Dec1985
21	FAJS	JOHANNESBURG	every 6 hours	
22	PANC	ANCHORAGE	every 6 hours	
23	CYYZ	TORONTO	every 6 hours until 17/11/1981; then every 3 hours	
24	CYVR	VANCOUVER	every 6 hours until 26/3/1979; then every 3 hours	
25	KMIA	MIAMI	every 6 hours until 20/3/1979; then every 3 hours	
26	KATL	ATLANTA	every 6 hours	
27	KDFW	DALLAS FORT WORTH	every 6 hours until end March 1979; then every 3 hours	
28	KLAX	LOS ANGELES	every 6 hours	
29	KMEM	MEMPHIS		hourly
30	KIAD	WASHINGTON DULLES		hourly
31	KIND	INDIANAPOLIS		hourly
32	KSFO	SAN FRANCISCO	every 6 hours	
33	KEWR	NEWARK		hourly
34	KORD	CHICAGO/O'HARE		hourly
35	KJFK	NEW YORK/JOHN F. KENNEDY	every 6 hours	
36	TFFR	LE RAIZET		every 3 hours
37	TFFF	LE LAMENTIN		every 3 hours
38	SAEZ	BUENOS AIRES EZEIZA AERO	every 6 hours until May 1985; then every 3 hours	
39	PHNL	HONOLULU	every 6 hours	

40	NZAA	AUCKLAND	every 6 hours	
41	YBBN	BRISBANE	every 6 hours	
42	YSSY	SYDNEY	every 6 hours	
43	YMML	MELBOURNE		every 3 hours
44	RPLL	MANILLA	every 6 hours	

Appendix B Approximate Height/Pressure Correspondence

This table shows an approximate conversion between pressure level P, used in the SSFM and altitude, z.

Level	P/hPa	z/m
00	1014.50	0
01	1014.20	3
02	1013.59	8
03	1012.98	13
04	1012.37	18
05	1011.47	26
06	1010.28	36
07	1009.09	46
08	1007.89	56
09	1006.10	72
10	1003.72	92
11	1001.34	113
12	998.95	133
13	996.29	156
14	993.35	182
15	990.41	207
16	987.46	233
17	984.23	261
18	980.70	292
19	977.18	323
20	973.65	354
21	969.61	389
22	965.04	430
23	960.48	470
24	955.91	511
25	951.22	553
26	946.40	597
27	941.58	640
28	936.76	684
29	931.82	729
30	926.74	776
31	921.67	822
32	916.60	869
33	911.40	918
34	906.07	967
35	900.75	1017
36	895.42	1068
37	889.97	1119
38	884.39	1172
39	878.81	1226
40	873.23	1279
41	867.52	1335
42	861.69	1391
43	855.86	1449

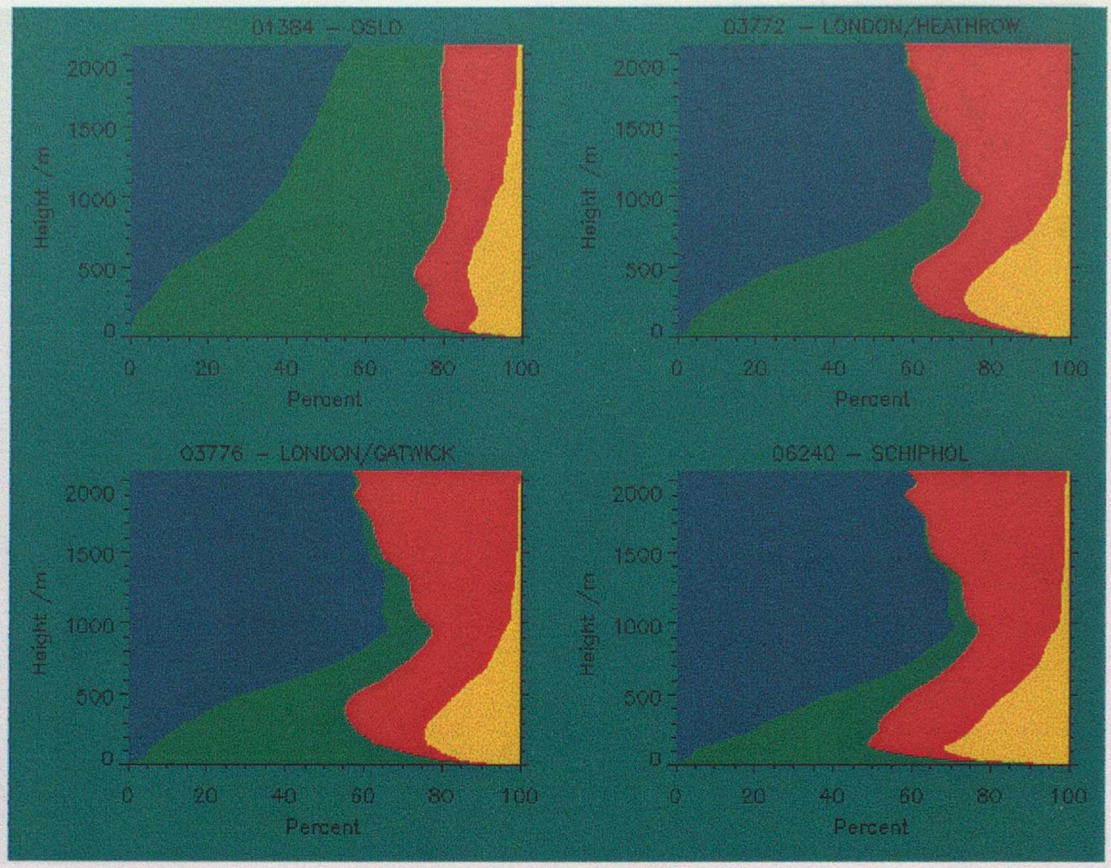
44	850.02	1506
45	843.94	1566
46	837.60	1629
47	831.25	1693
48	824.91	1757
49	817.94	1827
50	810.33	1905
51	802.72	1984
52	795.11	2063

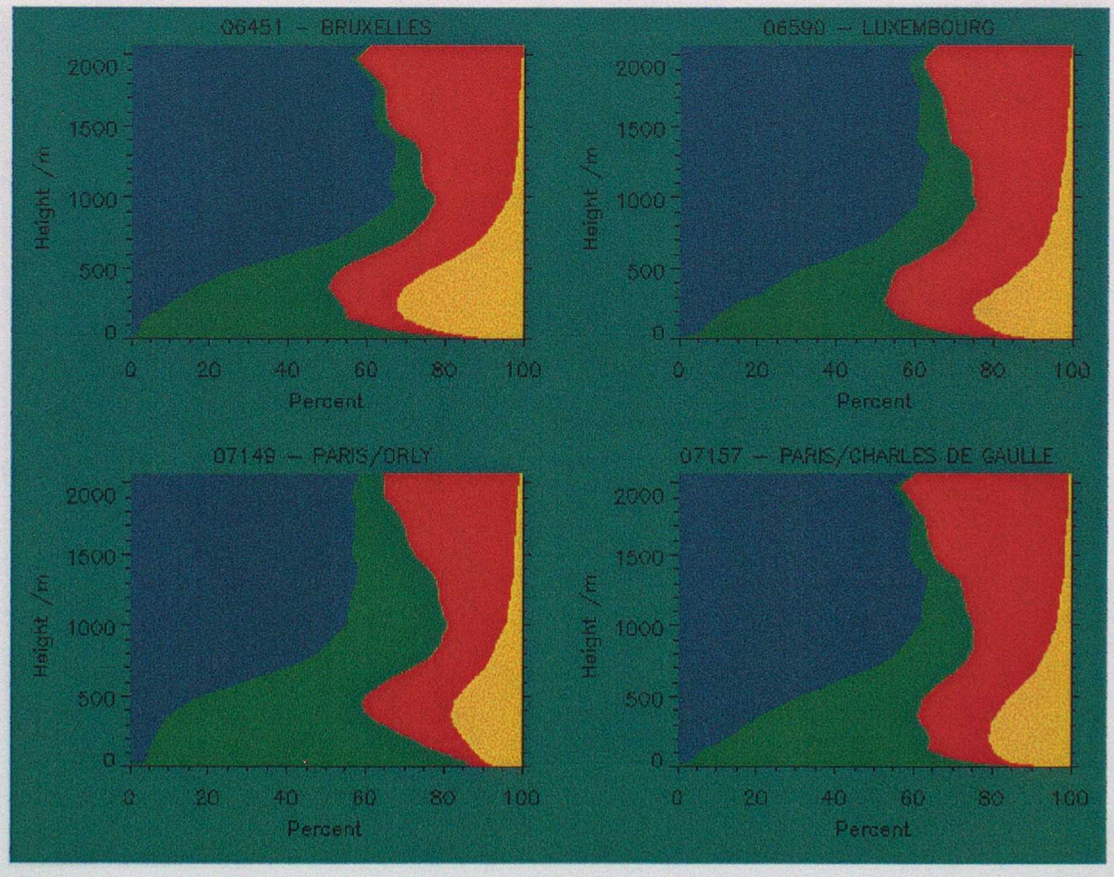
Appendix C WVBC Vertical Profiles

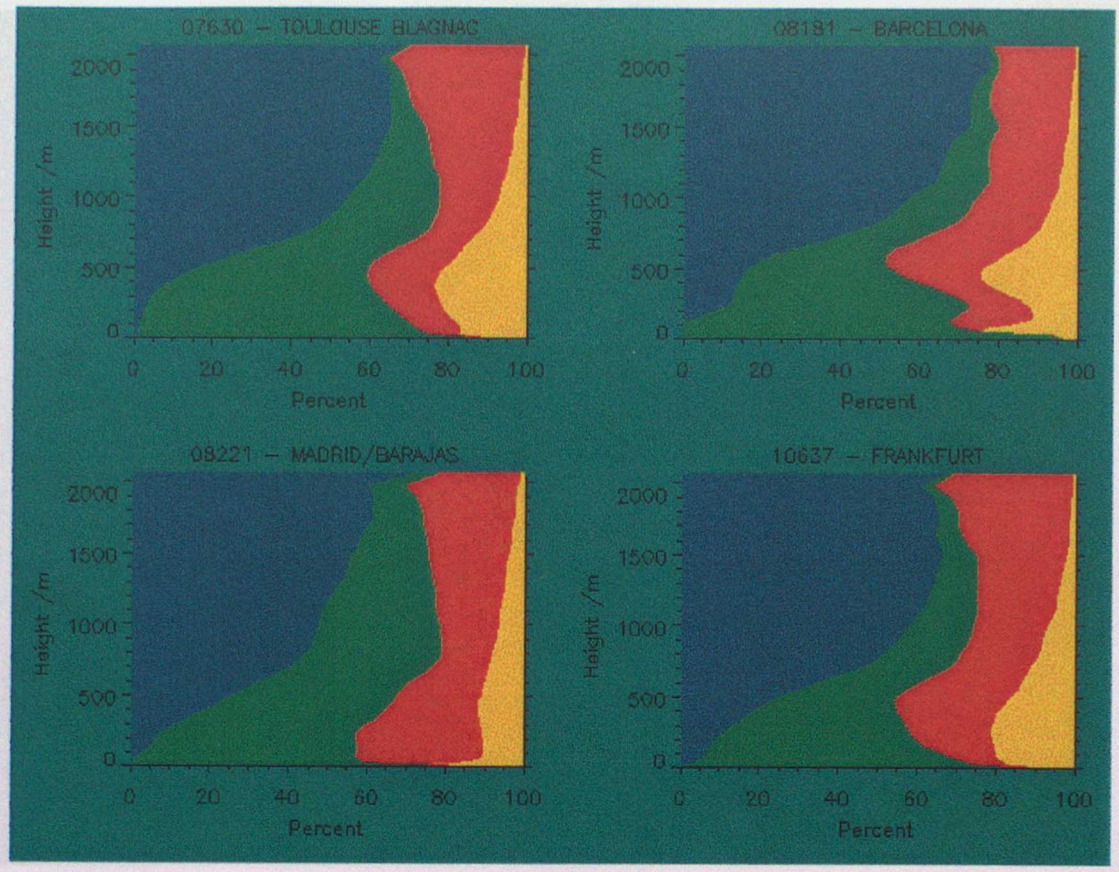
In these figures the colours correspond to WVBC in the following way:

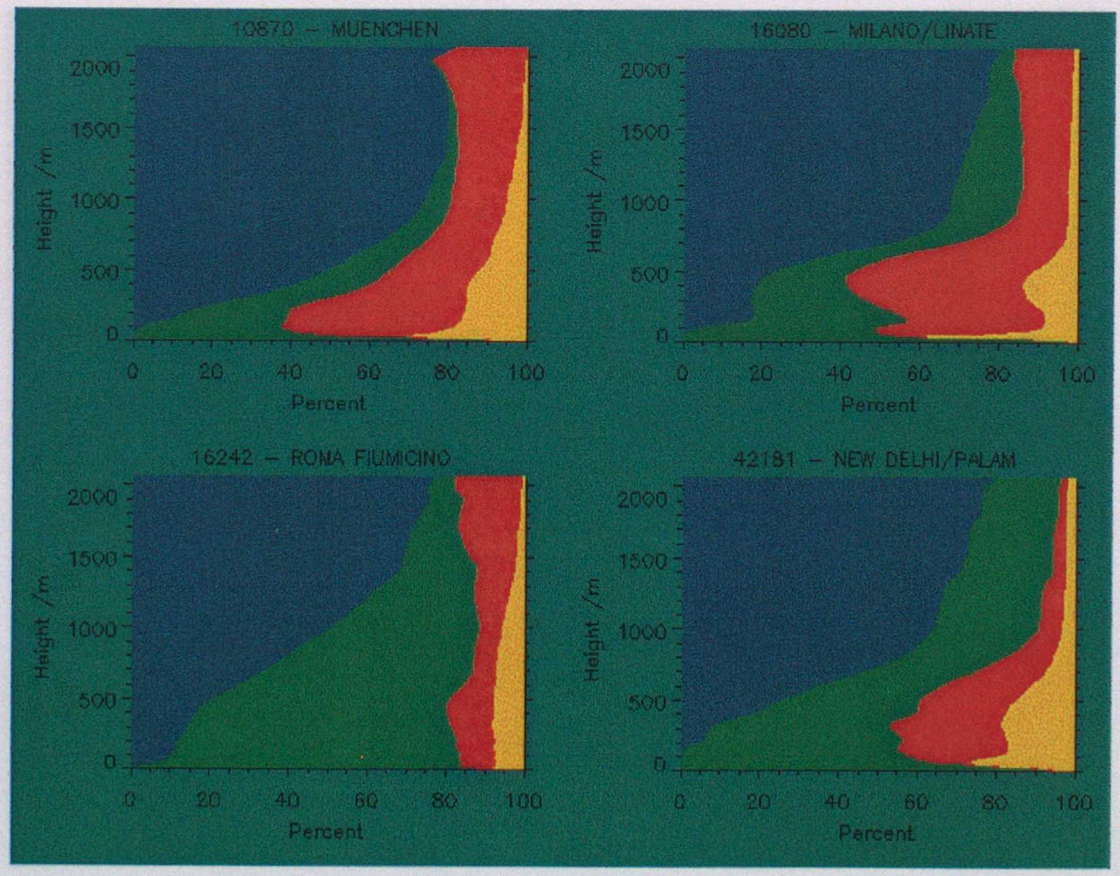
Blue – Null Class
Green – Turbulence Class
Red – Stable Stratification Class
Yellow – Wind Shear Class

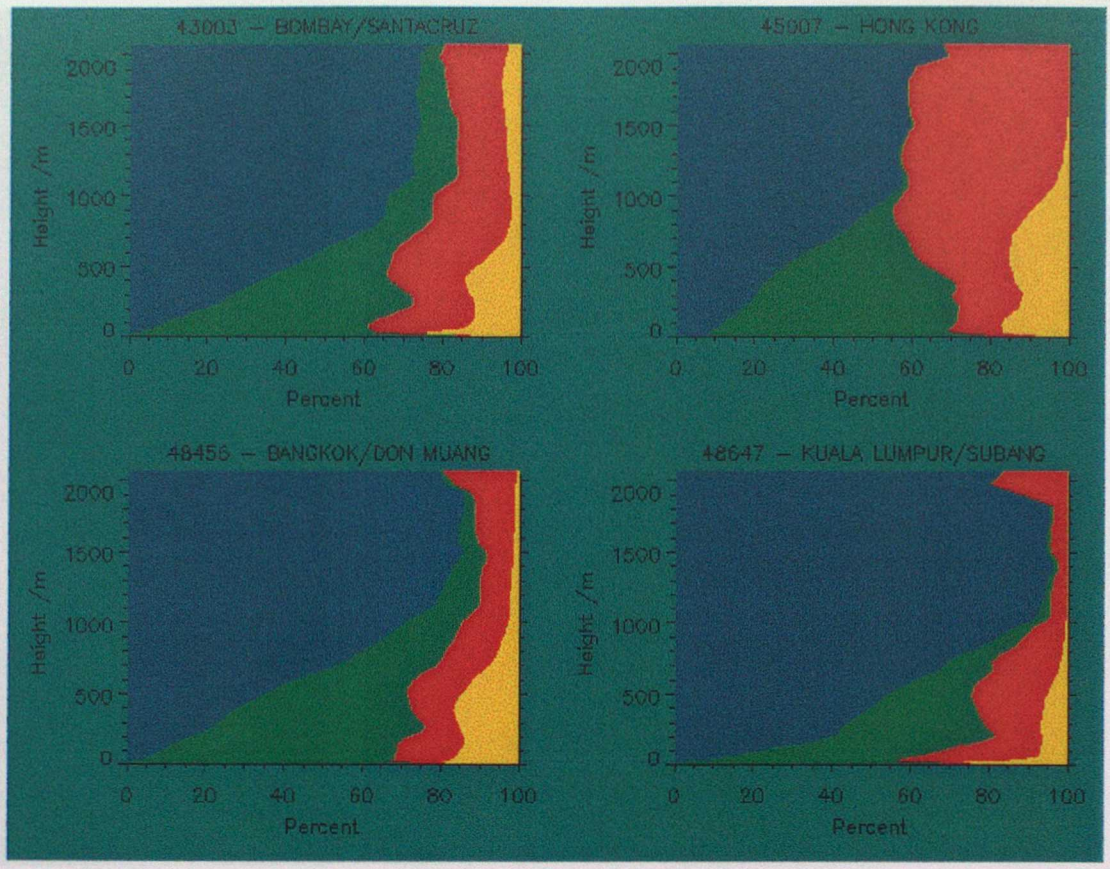
As described in section 5, the horizontal extent of each colour gives the percentage of time that a given weather class is found at that height. The title above each plot gives the WMO station code and the name of the site. The plots are arranged in order of increasing WMO number.

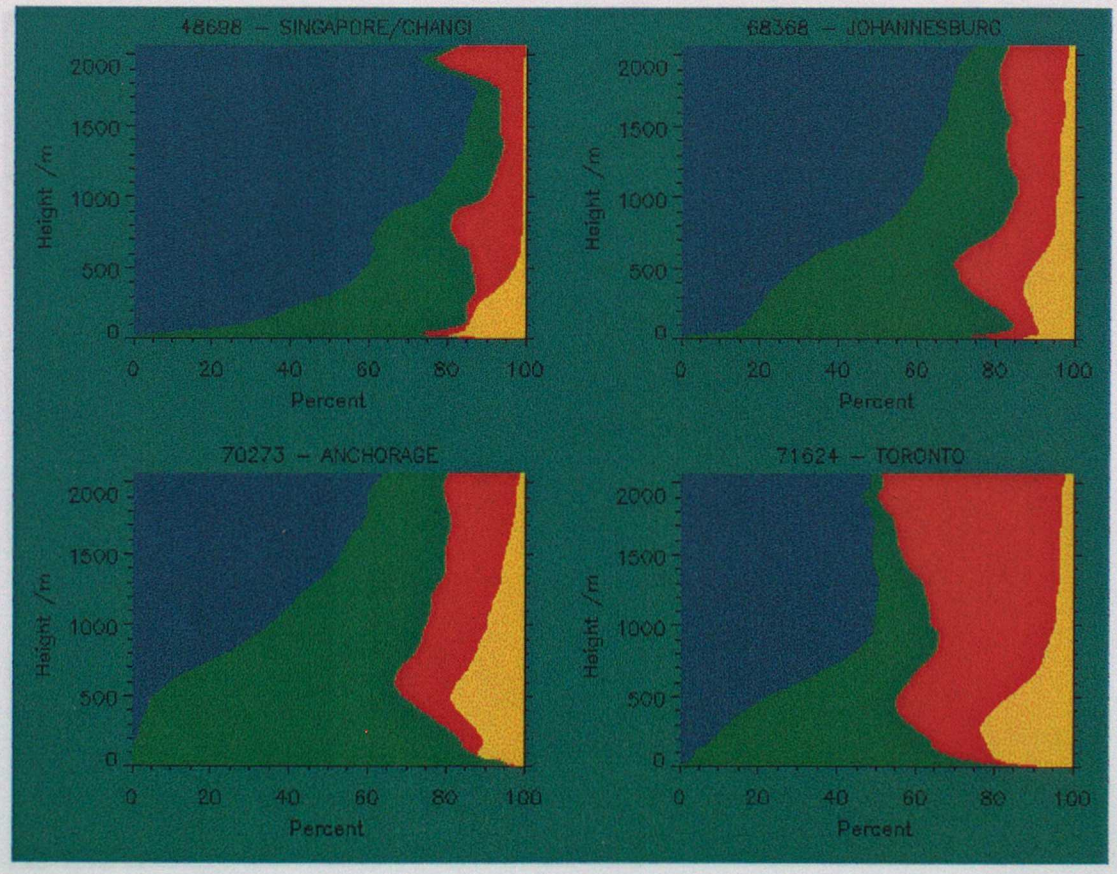

01384 – OSLO
03772 – LONDON/HEATHROW
03776 – LONDON/GATWICK
06240 – SCHIPHOL
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100

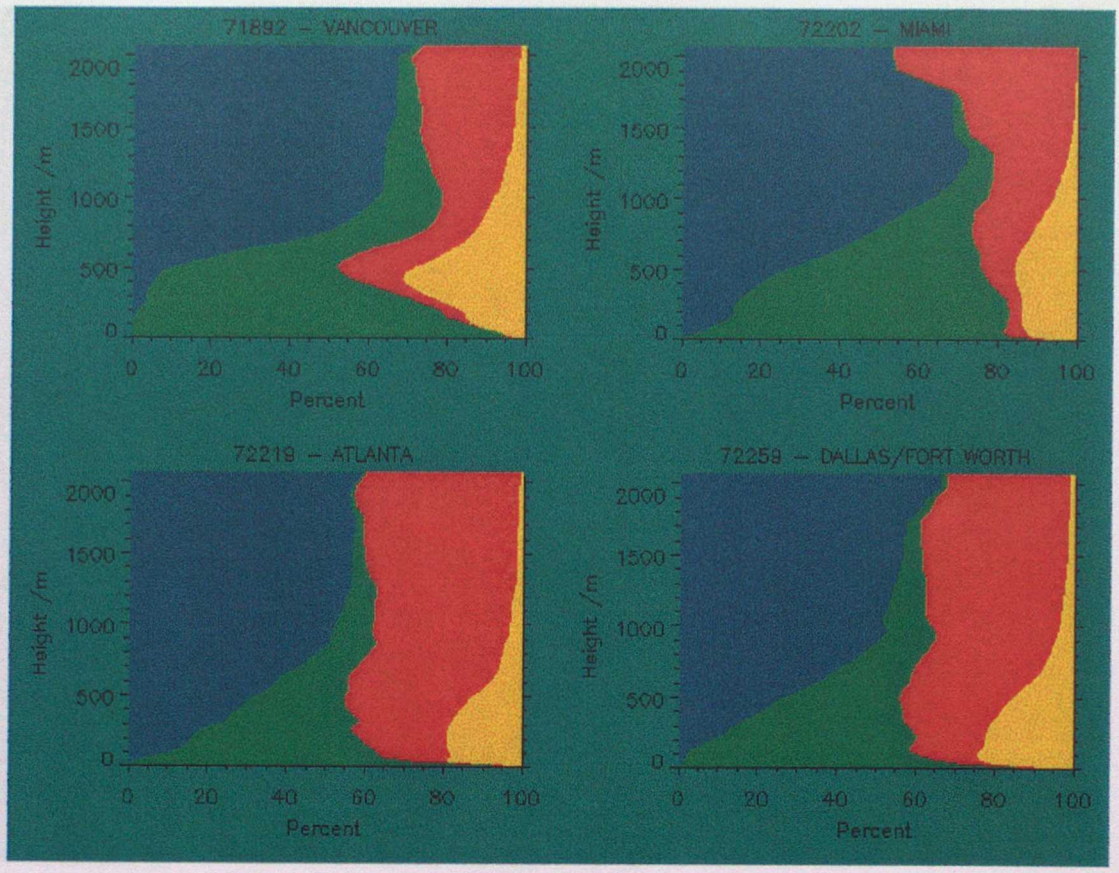

06451 – BRUXELLES
06590 – LUXEMBOURG
07149 – PARIS/ORLY
07157 – PARIS/CHARLES DE GAULLE
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100

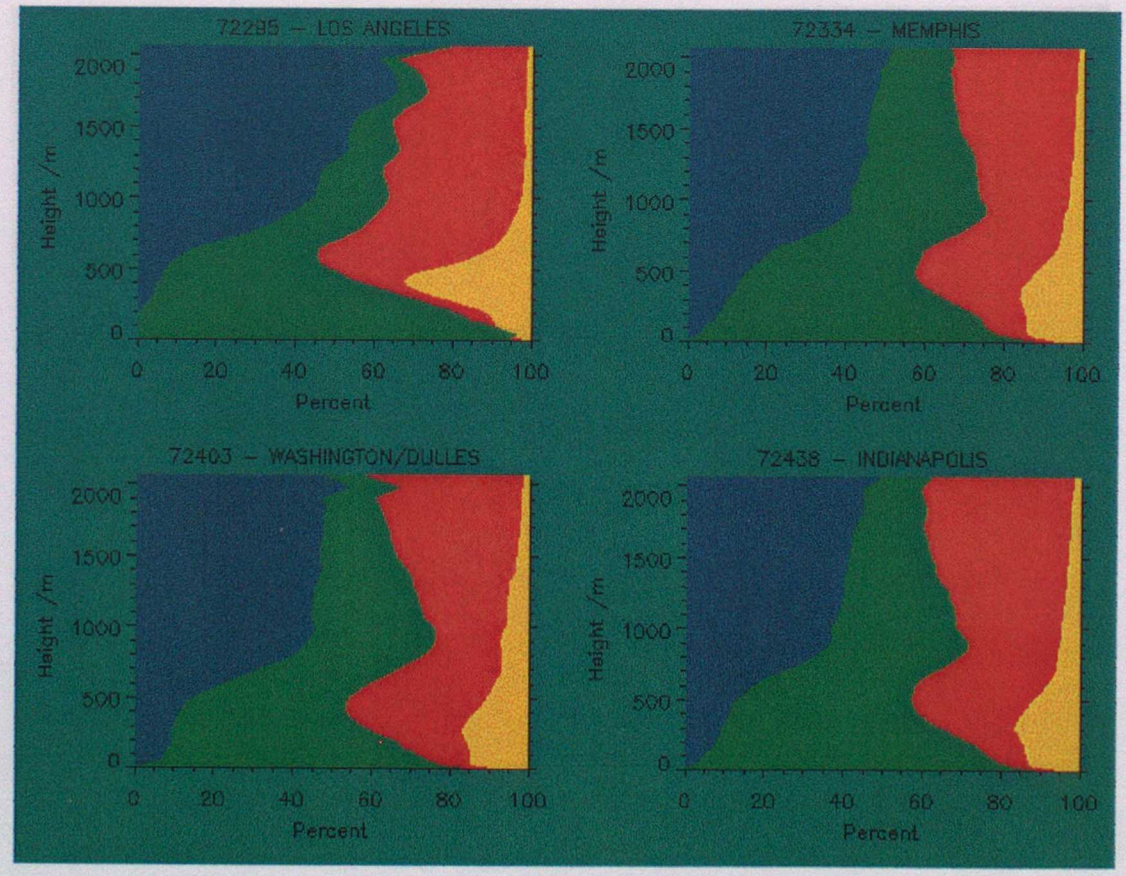

07630 – TOULOUSE BLAGNAC
08181 – BARCELONA
08221 – MADRID/BARAJAS
10637 – FRANKFURT
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100

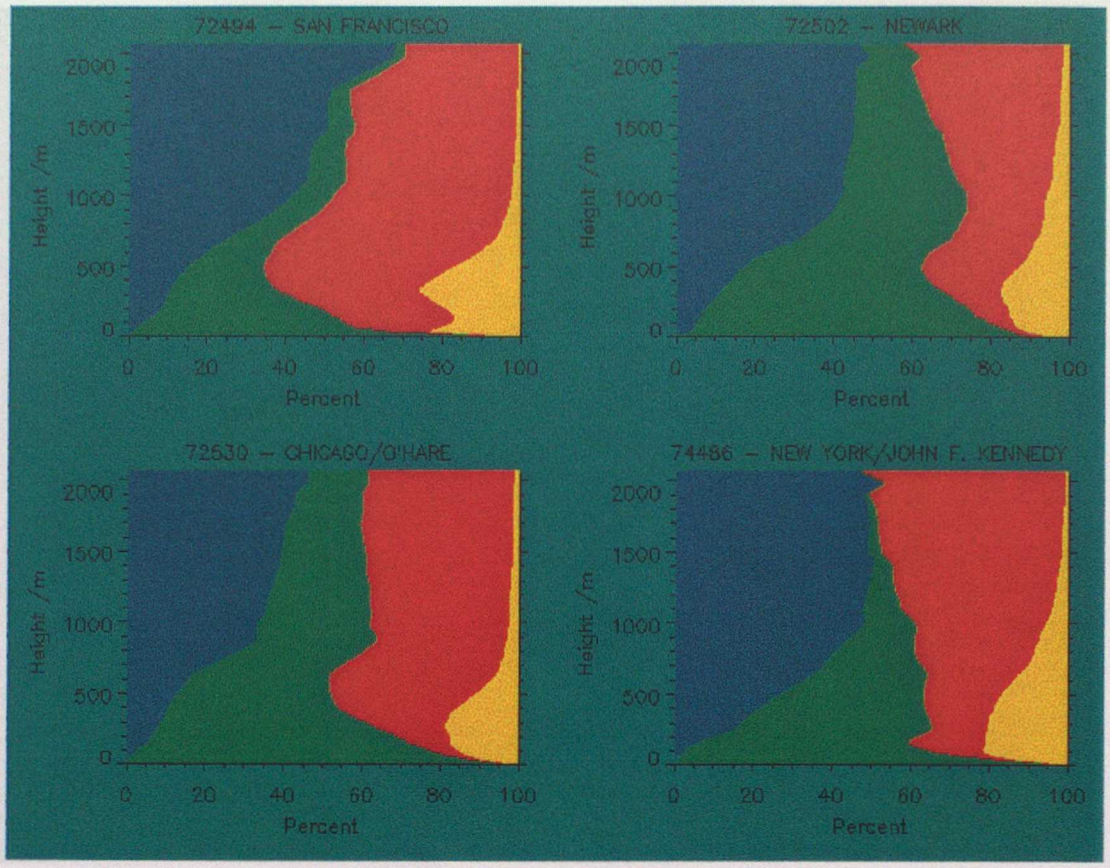

10870 – MUENCHEN
16080 – MILANO/LINATE
16242 – ROMA FIUMICINO
42181 – NEW DELHI/PALAM
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100

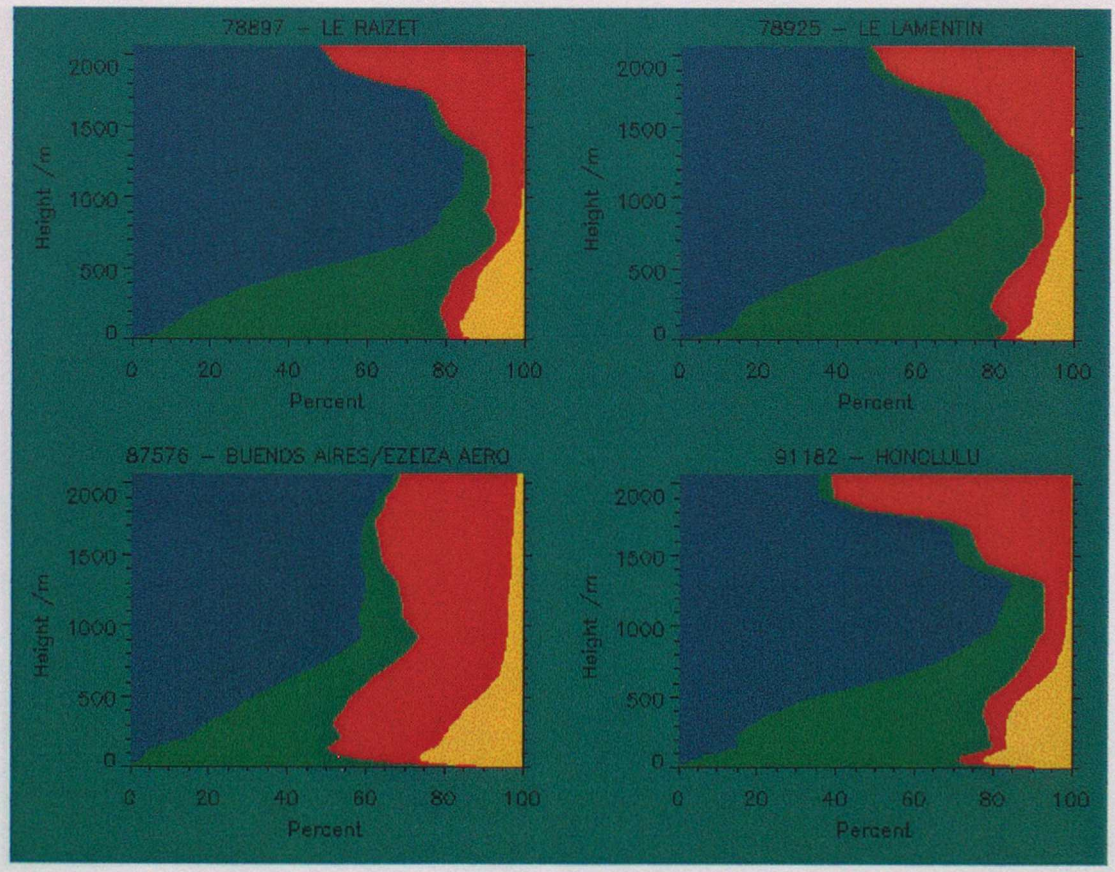

43003 – BOMBAY/SANTACRUZ
45007 – HONG KONG
48456 – BANGKOK/DON MUANG
48647 – KUALA LUMPUR/SUBANG
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100

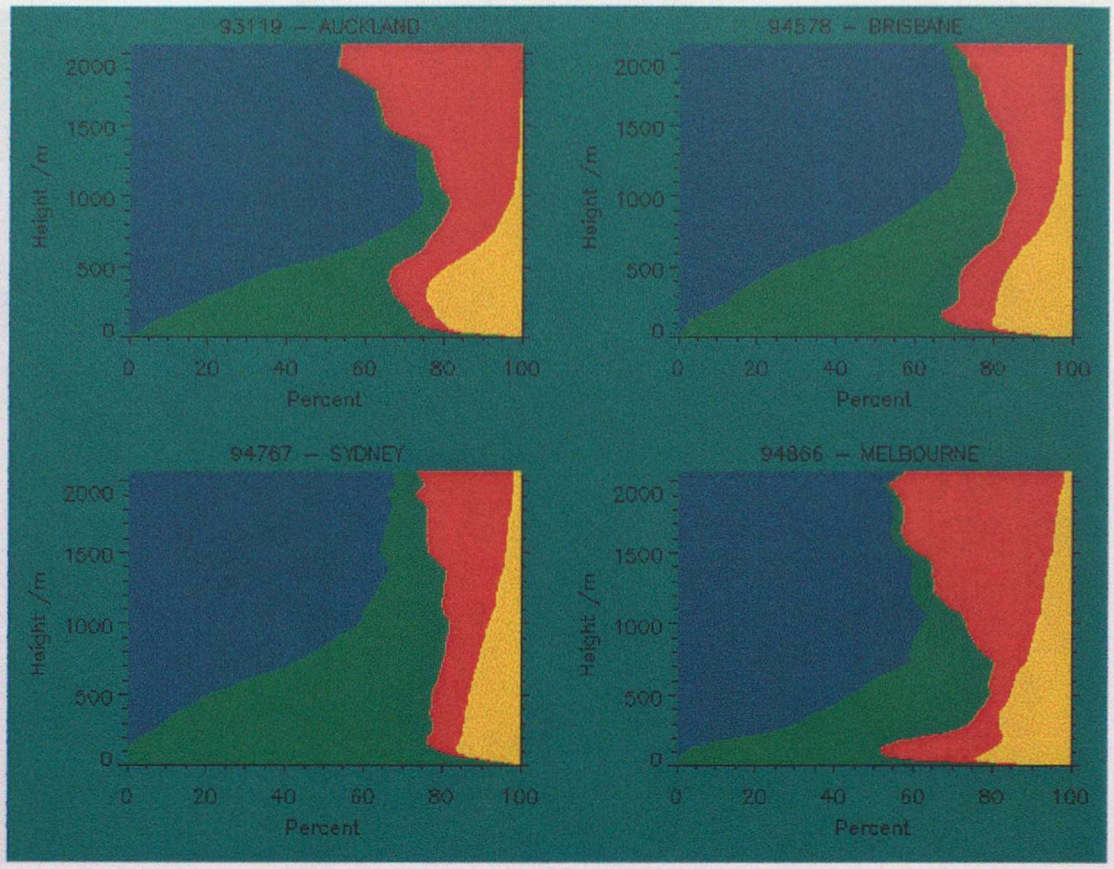

48698 – SINGAPORE/CHANGI
68368 – JOHANNESBURG
70273 – ANCHORAGE
71624 – TORONTO
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100

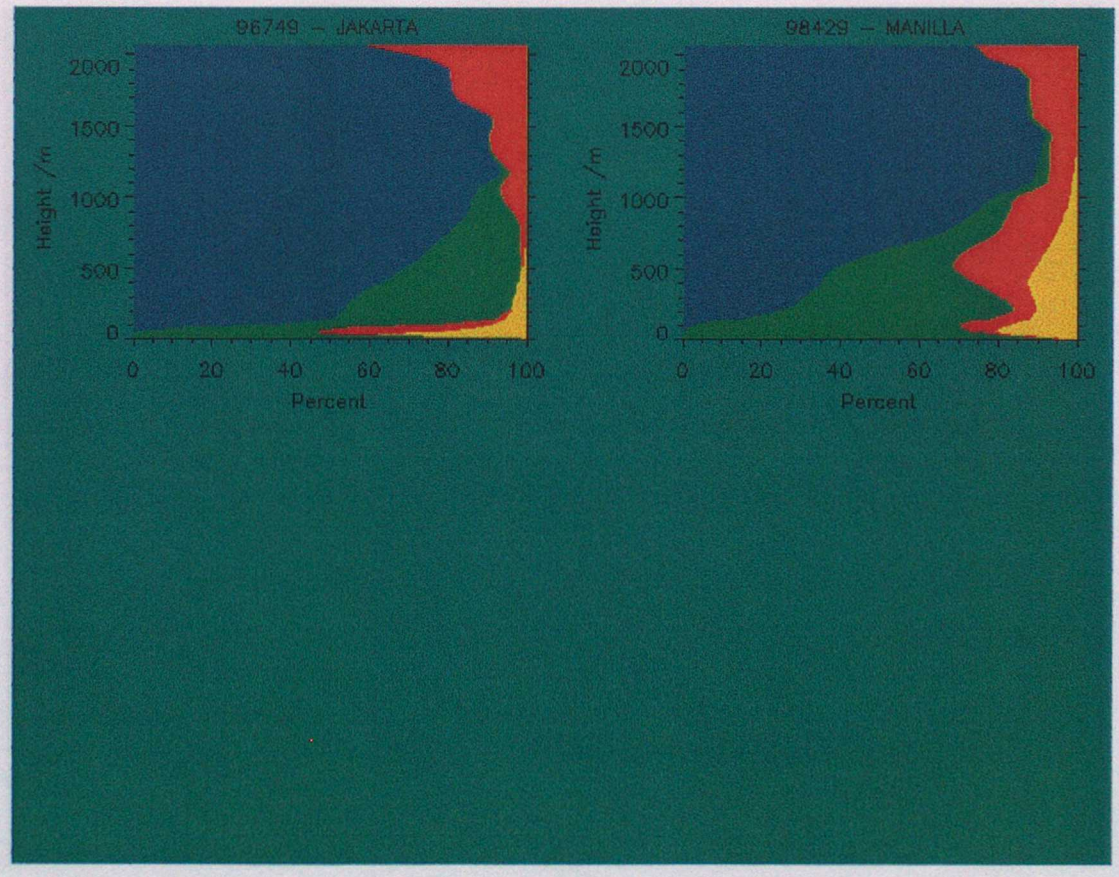

71892 – VANCOUVER
72202 – MIAMI
72219 – ATLANTA
72259 – DALLAS/FORT WORTH
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100


72285 – LOS ANGELES
72334 – MEMPHIS
72403 – WASHINGTON/DULLES
72438 – INDIANAPOLIS
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100


72494 – SAN FRANCISCO
72502 – NEWARK
72530 – CHICAGO/O'HARE
74486 – NEW YORK/JOHN F. KENNEDY
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100

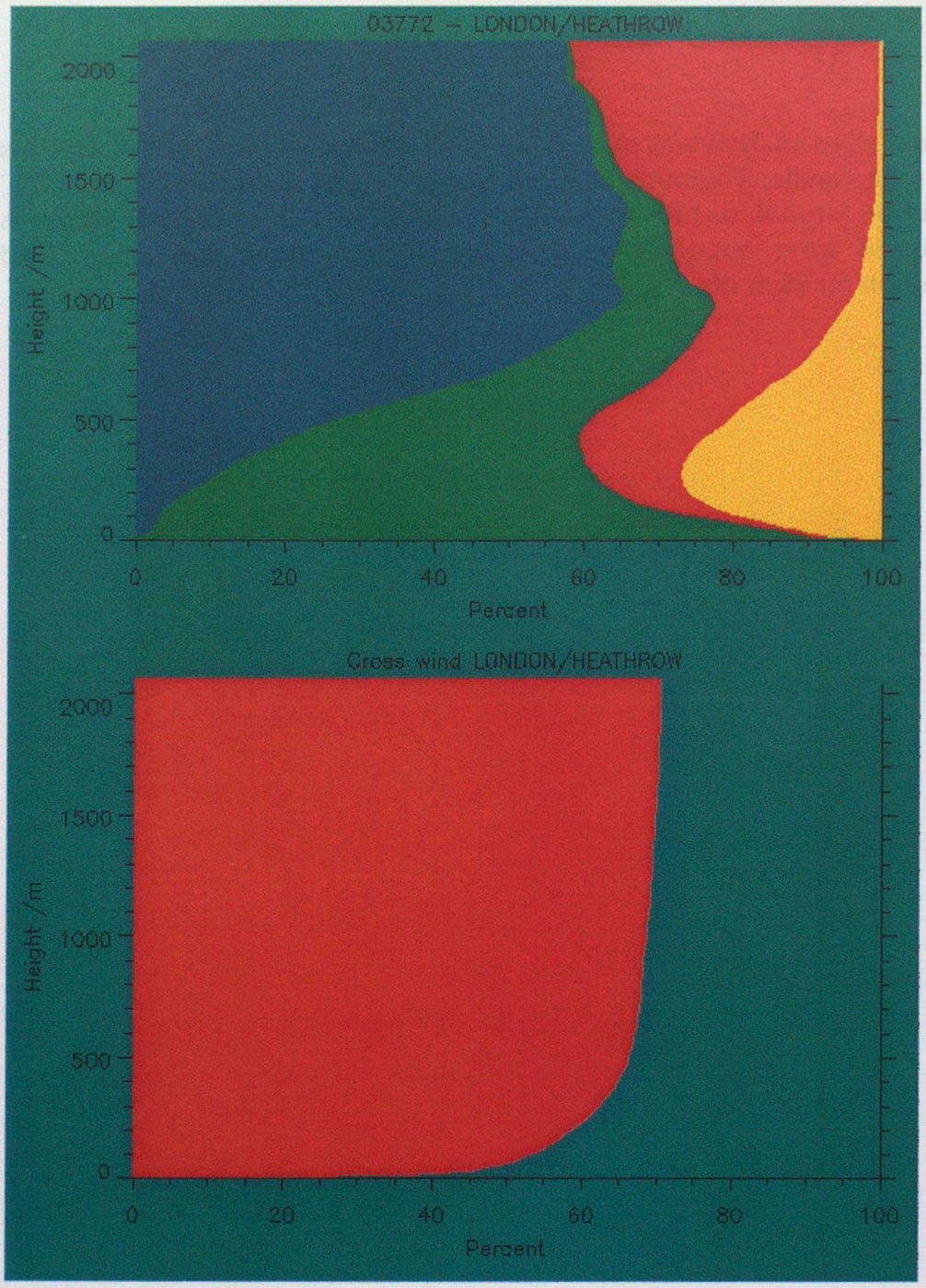

78897 – LE RAIZET
78925 – LE LAMENTIN
87576 – BUENOS AIRES/EZEIZA AERO
91182 – HONOLULU
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100

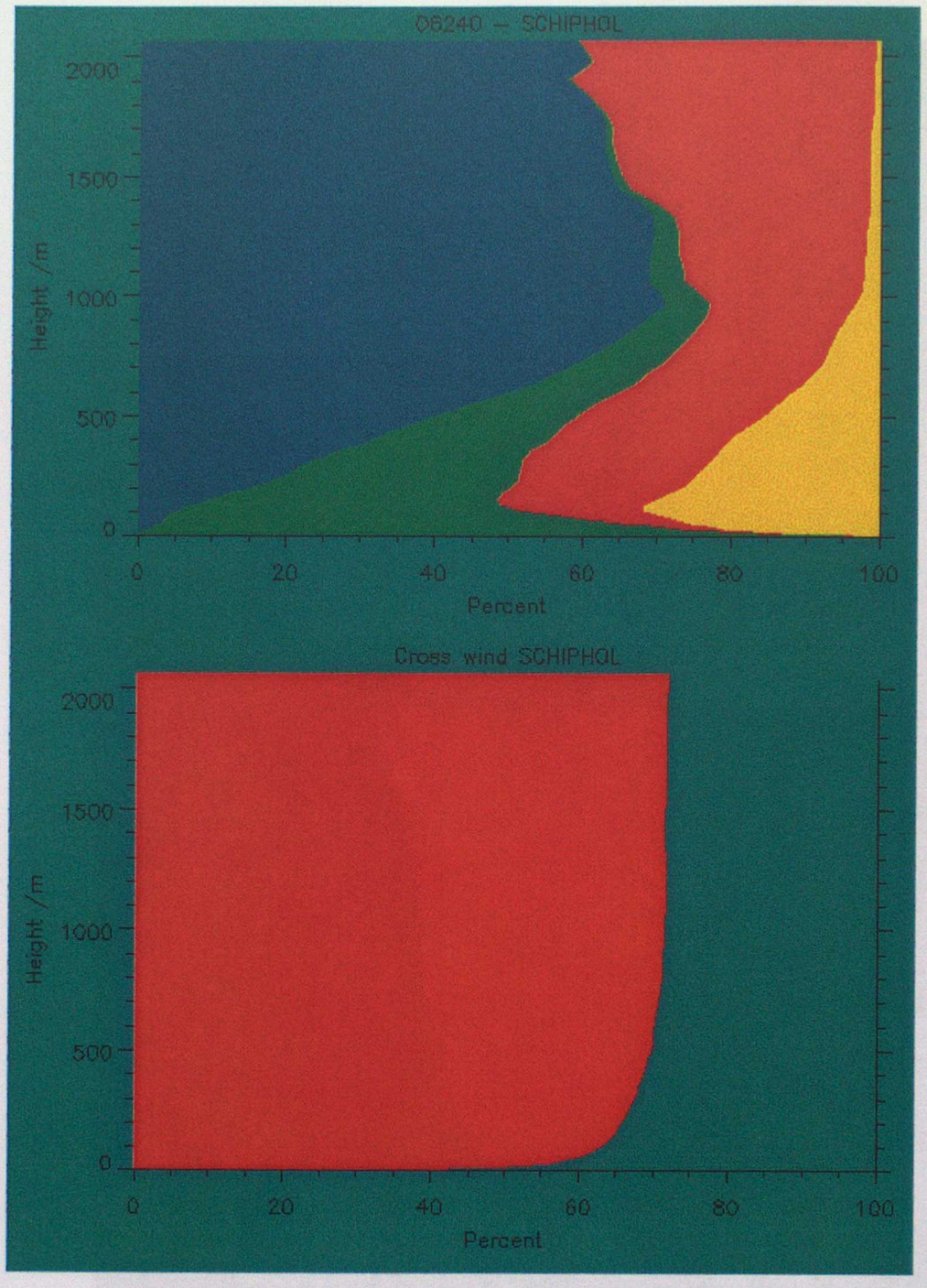

93119 – AUCKLAND
94578 – BRISBANE
94767 – SYDNEY
94866 – MELBOURNE
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100

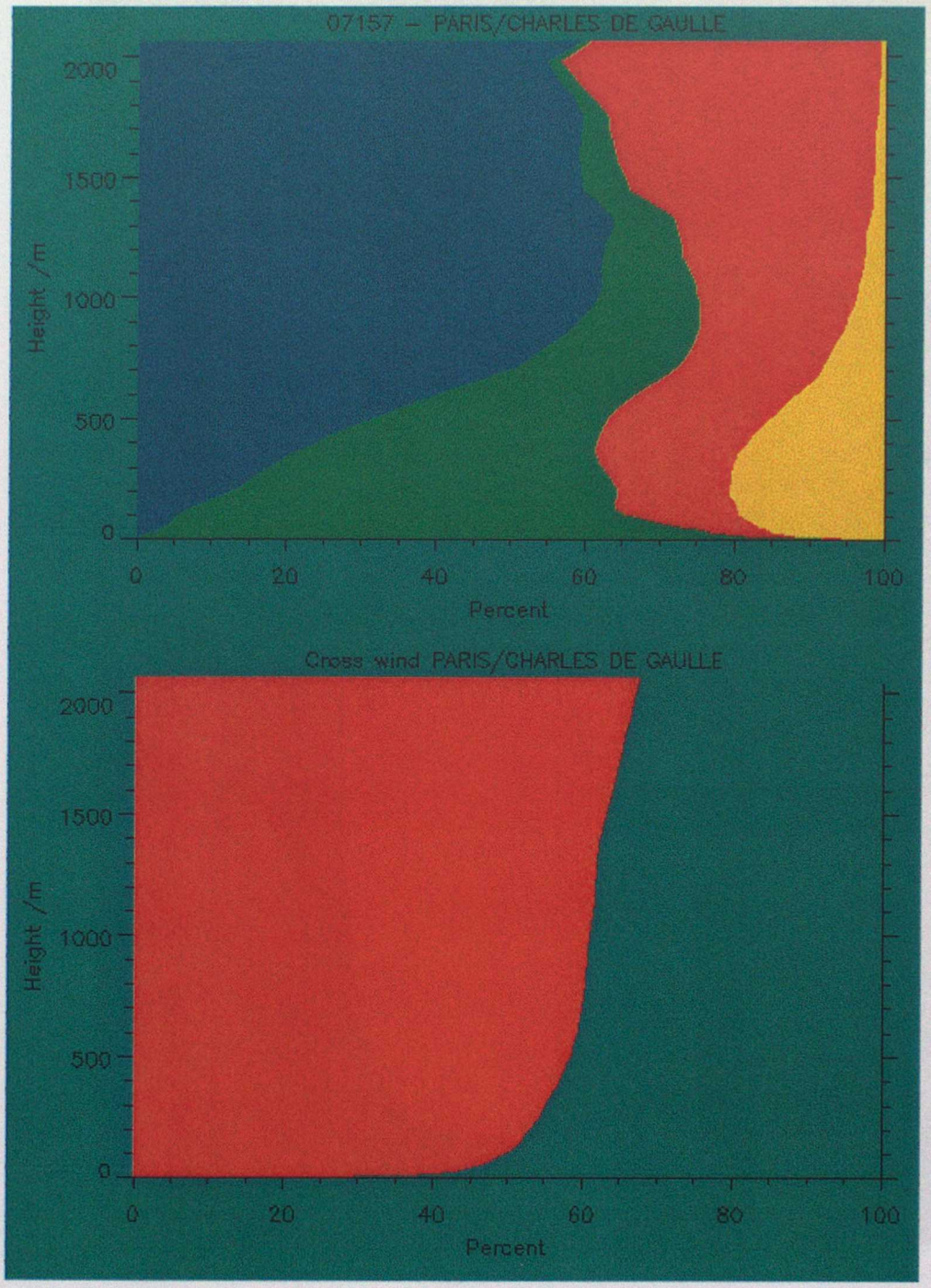

96749 – JAKARTA
98429 – MANILLA
Height /m
Percent
0
500
1000
1500
2000
0
20
40
60
80
100

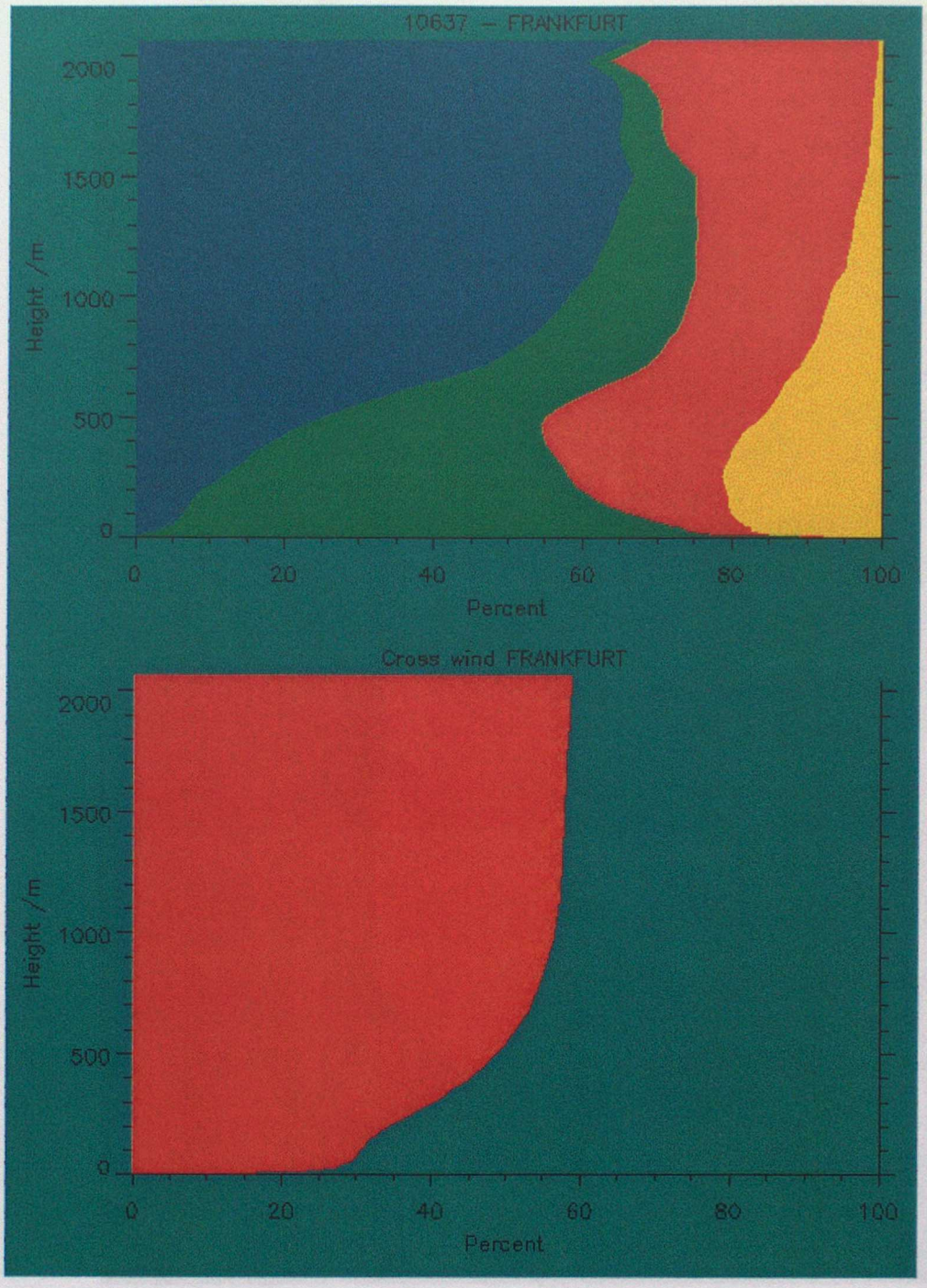
Appendix D Cross Wind WVBC Vertical Profiles

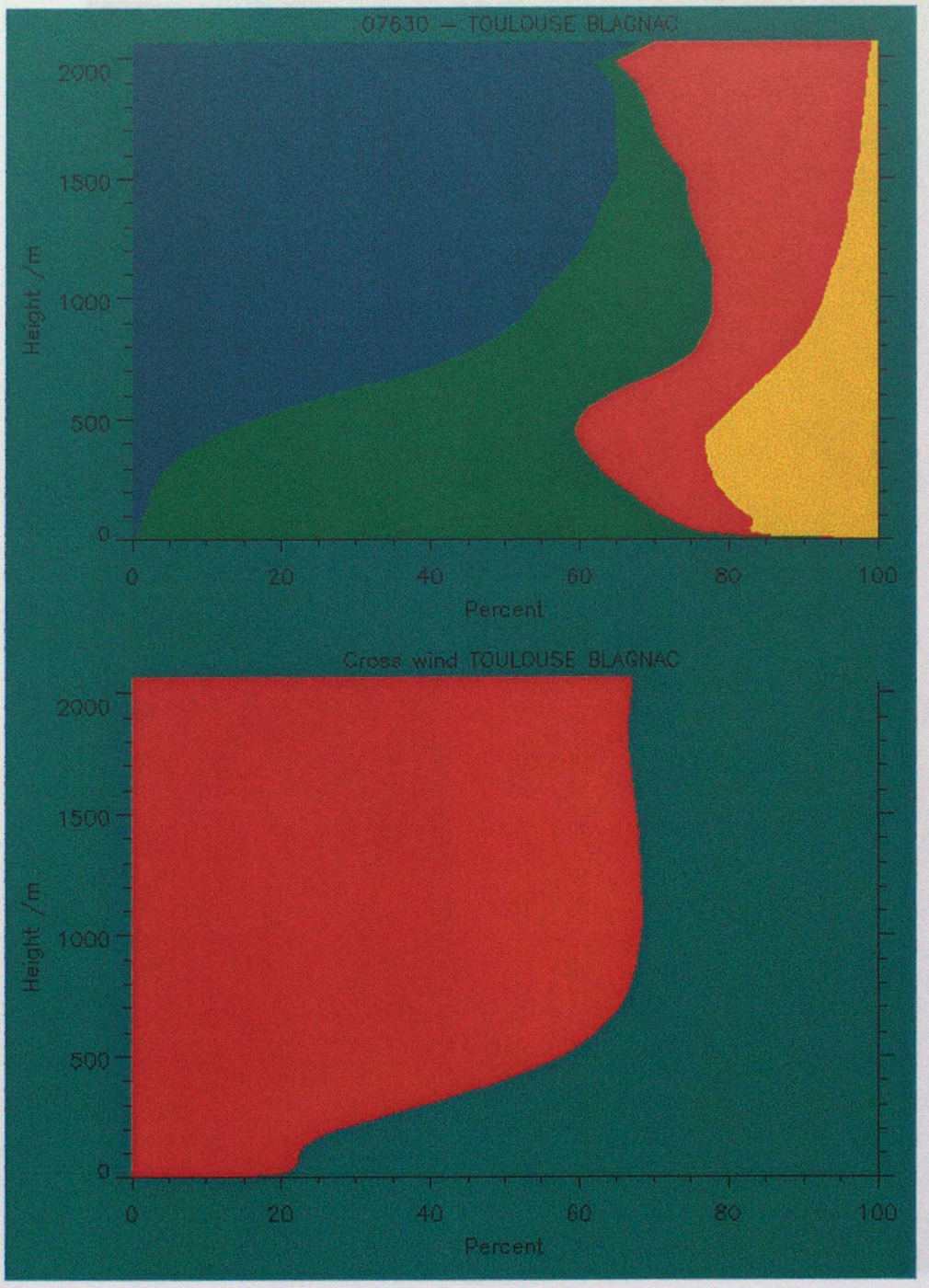
The cross wind analysis was carried out for London Heathrow, Frankfurt, Paris Charles de Gaulle, Toulouse and Amsterdam Schiphol airports. The WVBC distribution for null, turbulence, stable stratification and wind shear classes is reproduced from appendix C for convenience, above the cross wind distribution for each site.


03772 – LONDON/HEATHROW
2000
1500
1000
500
0
Height /m
0
20
40
60
80
100
Percent
Cross wind LONDON/HEATHROW
2000
1500
1000
500
0
Height /m
0
20
40
60
80
100
Percent


06240 – SCHIPHOL
2000
1500
1000
500
0
Height /m
0
20
40
60
80
100
Percent
Cross wind SCHIPHOL
2000
1500
1000
500
0
Height /m
0
20
40
60
80
100
Percent

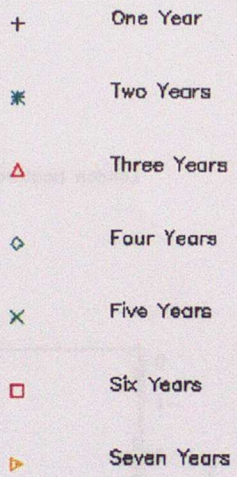

07157 – PARIS/CHARLES DE GAULLE
2000
1500
1000
500
0
Height /m
0
20
40
60
80
100
Percent
Cross wind PARIS/CHARLES DE GAULLE
2000
1500
1000
500
0
Height /m
0
20
40
60
80
100
Percent

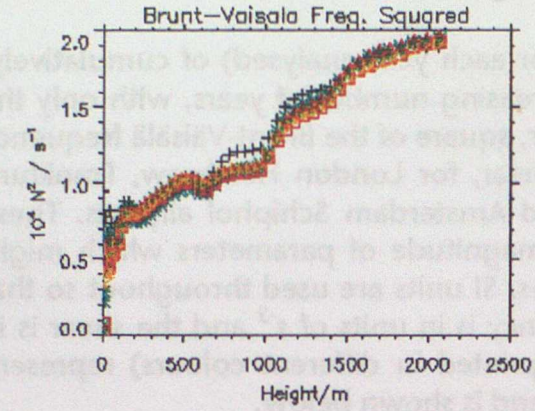

10637 – FRANKFURT
2000
1500
1000
500
0
Height /m
0
20
40
60
80
100
Percent
Cross wind FRANKFURT
2000
1500
1000
500
0
Height /m
0
20
40
60
80
100
Percent

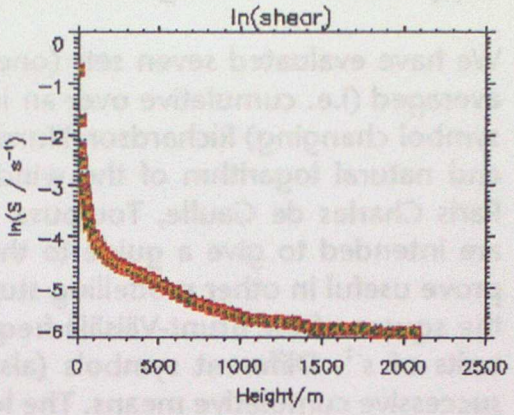

07630 – TOULOUSE BLAGNAC
2000
1500
1000
500
0
Height /m
0
20
40
60
80
100
Percent
Cross wind TOULOUSE BLAGNAC
2000
1500
1000
500
0
Height /m
0
20
40
60
80
100
Percent

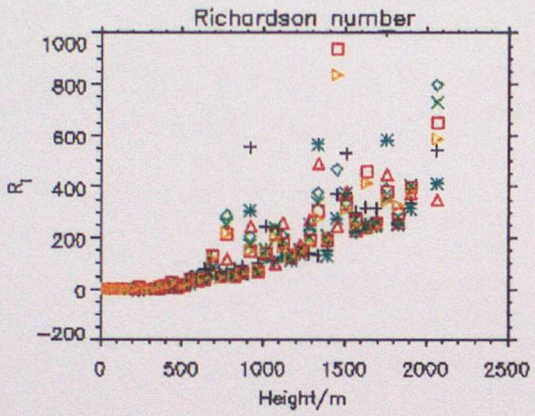
Appendix E Averaged Meteorological Parameter Vertical Profiles

We have evaluated seven sets (one for each year analysed) of cumulatively-averaged (i.e. cumulative over an increasing number of years, with only the symbol changing) Richardson Number, square of the Brunt-Väisälä frequency and natural logarithm of the wind shear, for London Heathrow, Frankfurt, Paris Charles de Gaulle, Toulouse and Amsterdam Schiphol airports. These are intended to give a guide to the magnitude of parameters which might prove useful in other modelling studies. SI units are used throughout so that the square of the Brunt-Väisälä frequency is in units of s^{-2} and the shear is in units of s^{-1}. Different symbols (also printed in different colours) represent successive cumulative means. The legend is shown below.

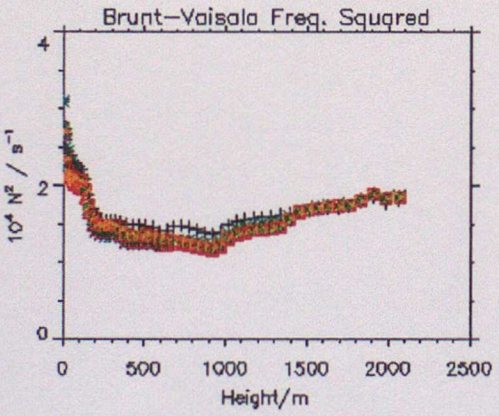


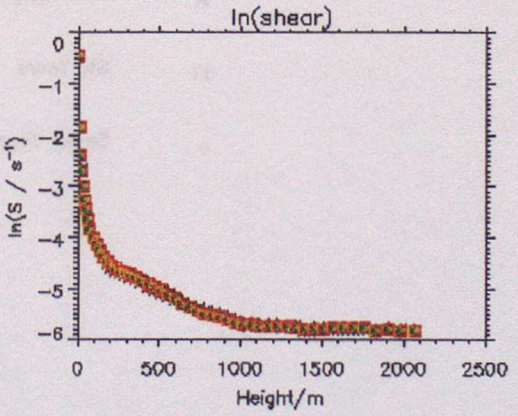


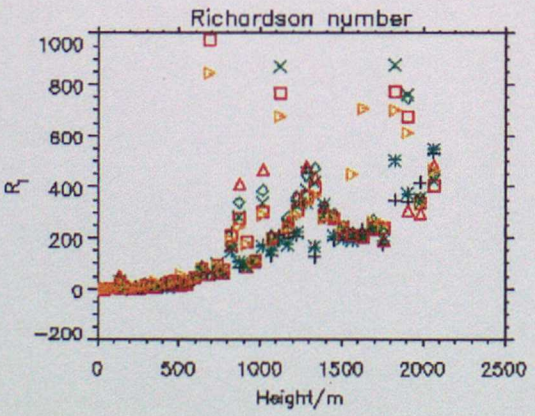




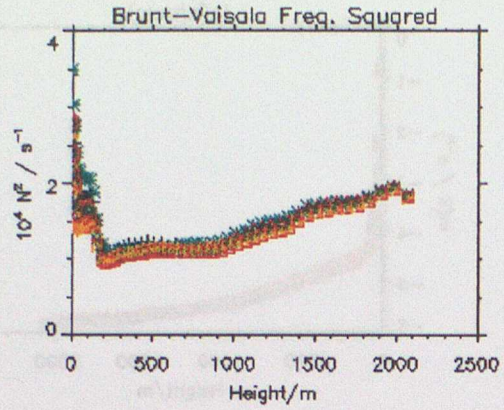
London Heathrow

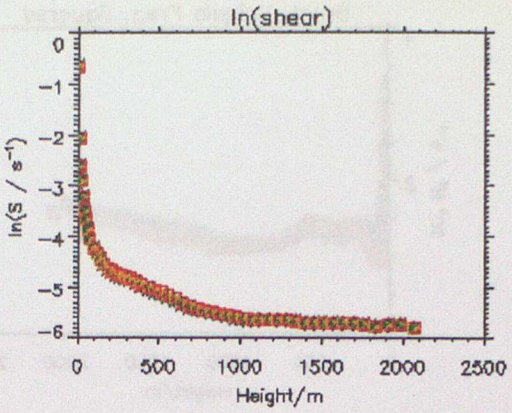


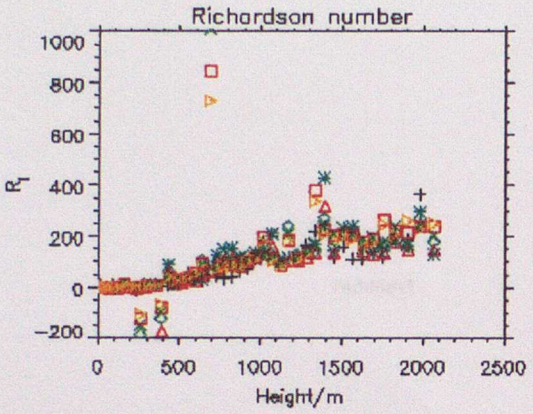




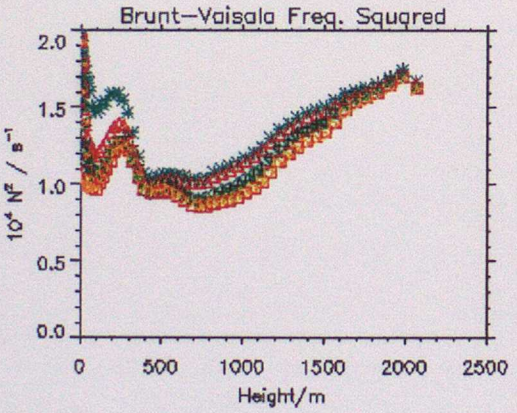
Amsterdam Schiphol

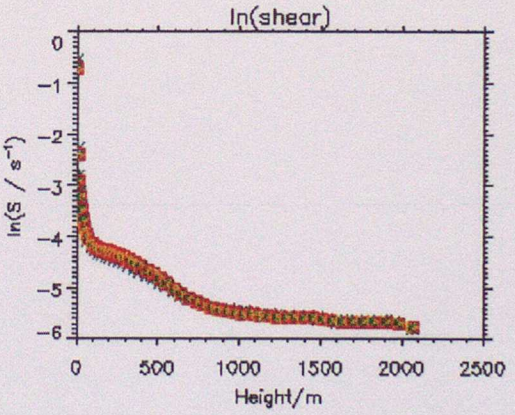


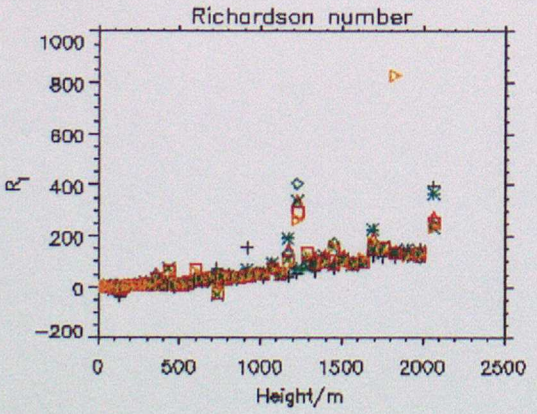




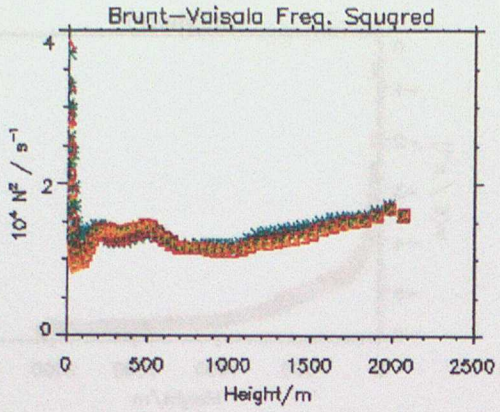
Paris Charles de Gaulle

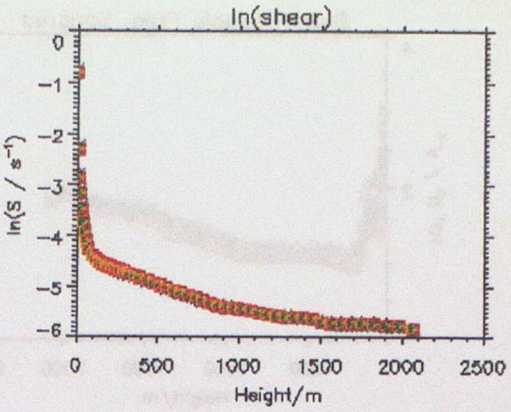


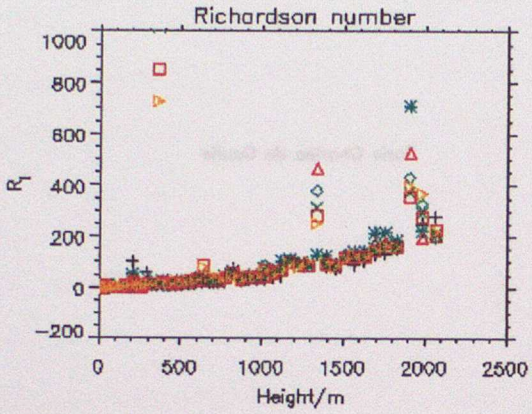




Toulouse


Brunt–Vaisala Freq. Squared
10^4 N^2 / s^{-1}
Height/m


ln(shear)
ln(S / s^{-1})
Height/m


Richardson number
R_i
Height/m

Frankfurt